Is LEO-based positioning with mega-constellations the answer for future equal-access localization?

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***Abstract*—Capital expenditures and indoor challenges are two of the main obstacles towards equal-access positioning services worldwide. Global Navigation Satellite Systems (GNSS) are not well functioning indoors and in some outdoor challenging scenarios, such dense forest canopies, or hilly terrains rich in vegetation, due, for example, to multipaths and low carrier-to-noise ratios. Terrestrial solutions can be nowadays used to complement GNSS, but they are typically costly to deploy with high coverage and do not offer equal access, for example in some low-revenue countries, in regions forbidding wireless 5G access due to health concerns, or in areas hard to reach with terrestrial infrastructure, such as deep jungle, desert areas with sandy dunes, or deep valleys/deep canyons. As many Low Earth Orbit (LEO) mega-constellations are emerging and their satellites are significantly closer to Earth than GNSS satellites, solutions based on LEO could complement GNSS. LEO-based communications are expected to be widespread in the next decade, and they will offer a global and-easy-to-access infrastructure, with the main costs to the end user coming from the receiver equipment. It is our assumption that future wireless receivers will support the integration of terrestrial and satellite infrastructure, and thus, the LEO-based positioning tasks could be mainly implemented as software adds-on on existing future receivers. Nevertheless, a closer proximity to Earth does not automatically mean stronger received signals or acceptable positioning accuracy, especially when the carrier frequencies of the new LEO signals are higher than those in GNSS. In here, we present a feasibility study of LEO-based equal-access localization, by looking at the current opportunities, benefits, and challenges of LEO mega-constellations used as signals of opportunities (SoO). We show that there is an unharnessed-yet potential of future LEO mega-constellations for equal-access localization, although several challenges are still to be overcome.**

I. INTRODUCTION

Position, Navigation, and Timing (PNT) services are mainly offered by GNSS with signals broadcast by satellites in Medium Earth Orbits (MEO). GNSS offer continuous, global, and free-of-charge positioning outdoors, with accuracies ranging from few meters to sub-meter levels. Despite being a successful technology for many applications, GNSS share some weaknesses, including the followings: i) accurate indoor localization solutions are not currently available due to weak-signal reception; ii) performance is poor in dense-urban canyons, areas with tunnels and areas dense foliage/trees, due to heavy multipath reflections and attenuation; iii) launching new MEO satellites for improved navigation capabilities has a long time-to-market and an expensive development cycle.

Our paper offers a feasibility study of the potential usage of LEO satellites mega-constellations for equal-access localization, by summarizing the opportunities provided by LEO signals, the unsolved challenges, as well as solutions to address these challenges. An illustrative scenario is also included, to compare LEO and MEO indoor coverage in terms of received Carrier-to-Noise ratio (C/N_0) and Geometric Dilution of Precision (GDOP), which are two known and widely used metrics in navigation community [1], [2].

II. LANDSCAPE OF LEO MEGA CONSTELLATIONS

Current LEO satellite constellations are meant for three main applications: i) enhanced mobile broadband applications (e.g., Starlink, Kuiper, OneWeb, ...); ii) Internet of Things applications and narrow-band communications (e.g., Astrocast, Myriota, ...); and iii) Earth Observation and surveillance applications (e.g., ICEYE, Satellogic, ...). Typically, LEO mega-constellations - with thousands of satellites each - are focusing on the first category, while the other two categories rely on few hundreds of satellites per constellation.

The future sky will support tens of thousands of LEO satellites [3], where one of its main benefits for positioning will be an increased visibility of satellites on Earth. While none of the above-mentioned constellations are specifically designed with positioning targets in mind, their wireless signals can be used as SoO for computing the PNT solution. SoO is a well-established concept for using wireless signal for something else than its initial purpose [4]. However, it has not been thoroughly investigated in the context of LEO positioning.

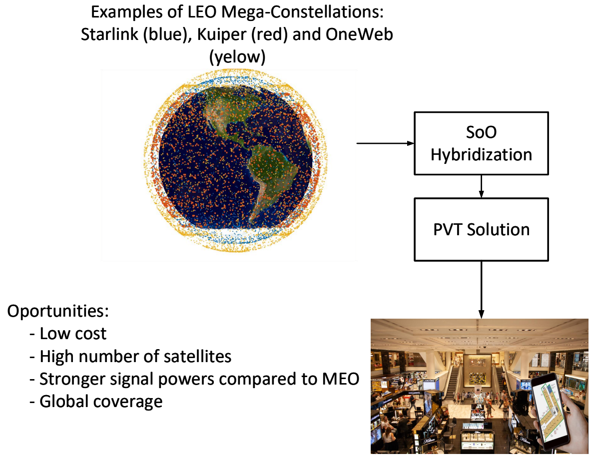

Fig. 1: Concept of LEO mega-constellations potential as SoO.

An illustrative block diagram of LEO constellations as SoO is shown in Fig. 1, with three of the existing LEO mega-constellations plotted as examples. The captured signals can be processed via a SoO-hybridization unit, operating with time, Doppler, or time-Doppler measurements. If the LEO satellite position is known, the PNT solution can be then formed via multilateration, in a similar manner as GNSS operations. Additional synchronization tasks might be necessary when LEO signals are not synchronized between them.

One can think about LEO SoO in three dimensions: i) time domain, harnessing the various LEO waveforms, transmitted at various frequencies/bandwidths; ii) angle/spatial domain; iii) Doppler/frequency domain, exploiting the high orbital speeds of the LEO satellites and the rich frequency spectrum. Most LEO satellites will be equipped with multi-antenna arrays, enabling beamforming [3] and spatio-temporal 'fingerprints' of antenna beams [5]. E.g., most signals coming from LEO constellations operate in Ku, K, or Ka frequency bands, namely at 12-40 GHz, where path losses are about 10-30 dB higher compared to L-band MEO GNSS. Higher carrier frequencies also increase the path losses, due atmospheric attenuation. Nevertheless, LEO satellites are functioning in orbits between 10 and 115 times closer to the Earth, which makes the overall path losses to be with up with 30 dB smaller than for a MEO signal operating at the same frequency. Thus, the opposite path-loss effects of higher carrier frequencies but closer proximity to Earth need careful investigation.

Another potential benefit of LEO as SoO for positioning is related to the capital expenditures (capex) to invest in a new positioning system. Such capex costs are three-fold: the infrastructure costs, usually the highest among the three parts, the receiver/user equipment costs, and the service/maintenance cost. Assuming that the existing infrastructures can be used at little/no cost, then LEO signals would have a clear cost advantage over other terrestrial localization solutions,e.g., relying on WiFi, Ultra-Wide Band (UWB), Bluetooth Low Energy (BLE), or cellular/5G-based positioning which require dense or ultra-dense infrastructure for a reasonable coverage. A thorough survey of existing indoor positioning techniques can be found in [6], yet all the methods surveyed rely on available indoor infrastructure, such as WiFi/BLE access points or some other form of Internet access.

In order to enable the access equality and to cover also regions with limited resources and lack of terrestrial wireless infrastructure, the use of signals coming from satellites offering global coverage is a very promising solution. In particular, 5G-based positioning would require significant investments in 5G infrastructure relying on dense and ultra-dense networks for good coverage especially with mm-wave signals. LEO mega constellations are, at the same time able to offer global coverage as well as shifting the burden of infrastructure costs from the end user to the system manufacturer, since the user will only require a receiver compatible with the considered frequency bands. LEO business models are still in the definition phase, with many proposals shifting the main revenue sources from customers/end-users to the investors. The main remaining costs for a LEO-based positioning would come from the receiver costs, where receiver processing should include the PNT computation based on one or several LEO mega-constellation signals. Receiver aspects in LEO-based positioning are further addressed in Section III.

Several challenges are still to be overcome towards the full potential of LEO as SoO. First, we address scenarios by comparing MEO and LEO capabilities in Section III and we detail the design aspects in the receiver processing part, with a focus also on the innovative concept of Multiple Input Multiple Output (MIMO) beamforming for positioning. Then we discuss the opportunities, challenges, and possible solutions for LEO-based indoor navigation (Section IV).

III. EXAMPLE SCENARIOS AND DESIGN CONSIDERATIONS

In order to analyze the LEO potential as SoO, several aspects need to be tackled. Few of these aspects are addressed in the next sub-sections, namely: i) an analysis of performance metrics in terms of C/N_0, number of visible satellites, and satellite geometry under a realistic indoor Non Line of Sight (NLOS) scenario; ii) a discussion on the receiver-design aspects in LEO-based signal processing; and iii) a brief description of the innovative concept of massive MIMO-based processing for positioning.

A. LEO potential - a case study

This sub-section presents a comparison of LEO and MEO-based performance metrics in terms of positioning. Two performance metrics were selected for this purpose: the indoor received C/N_0 and GDOP [1]. We used Starlink, Oneweb, and Kuiper as representatives of LEO constellations, operating at 12-20 GHz (Ku/K bands), and Galileo and GPS as representative of MEO constellations, operating at 1.575 GHz (L-band). In addition, the average number of visible satellites per Earth point and per constellation is also shown. The considered MEO GNSS constellations are at about 20000-23000 km altitude, while the LEO constellations are at altitudes of about 600 km, 1200 km and 300-600 km for Kuiper, Oneweb and Starlink, respectively. The C/N_0 is a well known metric in navigation community, referring at the signal-to-noise ratio in the desired bandwidth and thus measured in dB-Hz units; it basically measures how well a signal could be acquired and further processed indoors; the higher C/N_0, the better the acquisition. GDOP is a measure of how good the geometry of the satellites position is and readers can find its detailed definition for example in [1]; the smaller the GDOP, the better the geometry, and thus the better the positioning accuracy.

Fig. 2 gives a comparative example of the average C/N_0 in indoor and outdoor scenarios at 10^4 random user Earth locations for LEO/MEO signals. The path-loss simulator was based on the QuaDRiGa framework [7], which includes antenna-gain modeling, atmospheric delays, and multipath propagation. The constellation-orbit simulator relies on the MATLAB Satellite-Communications toolbox. The considered scenario is a dense urban scenario, with NLOS propagation. For comparative purposes, also the results for an outdoor scenario are shown. Each scenario consist on ten NLOS components. The scenario layout contains buildings up to 60 m height. The indoor receiver is considered to be at 10 m inside a building. The three selected LEO mega-constellations in Fig. 2 use Ku/K frequency bands ($12-20$ GHz), while GNSS constellations use L band (1.575 GHz). It is to be noted that some of the future LEO systems will use even higher carrier frequencies, moving towards the mmWave ranges. In Fig. 2, the LEO power reception is higher compared with MEO, showing better potential than GNSS for indoor reception. In this analysis, the Effective Isotropic Radiated Powers (EIRPs) for each satellite in the constellations were set to 59 dBm, 59 dBm,69.5 dBm,65 dBm and 69.1 dBm for Galileo, GPS, Kuiper, Oneweb, and Starlink, respectively. Outdoors, LEO C/N_0 levels are between 32-43 dBHz (Starlink has the highest C/N_0 due to the its lower orbital altitude, followed closely by Kuiper), while the C/N_0s for the considered MEO constellations are about 25-27 dBHz. Indoors, the gap between LEO and MEO C/N_0 is slightly lower than outdoors, but still noticeable: the received C/N_0 is about 17 dBHz and 16-19 dBHz for LEO and MEO, respectively. Therefore LEO constellations show a gain of up to 18 dB outdoors and up to 5 dB indoors. Fig. 2 also shows the mean number of satellites in view $\overline{\#Sat}$ for each one of the selected constellations indoors (those satellites with a higher or equal elevation to 10° from the specific user position and with a received power higher than the receiver sensitivity set to -150 dBm, which is a typical PNT receiver sensitivity). No specific antenna pattern was taken into account, as information about antenna patterns on-board LEO satellites is currently not available in public domain, but we have adopted a mathematical model of elevation-based angle-of-service for the beamforming part. For MEO constellations, the average number of satellites in view indoors is about 2, while for LEO this number is considerably bigger, showing a better coverage and excellent potential for multilateration (i.e., combining signals from multiple satellites to form a PNT solution): about 73, 694, and 344 for Kuiper, Oneweb and Starlink, respectively. In the constellation simulations we used the total planned number of satellites for each LEO mega-constellations, which are 7774, 47844, and 34408 for Kuiper, Oneweb and Starlink, respectively.

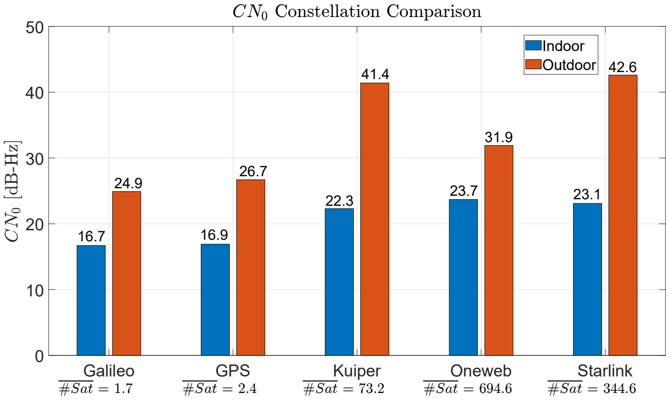

Fig. 2: Illustrative example of C/N_0 indoors for LEO vs MEO constellations.

Fig. 3 shows the GDOP comparison in the case of joint processing of multiple constellations: the comparison is between a combination of three LEO constellations (upper plot in Fig. 3) and a combination of four MEO constellations (bottom plot in Fig. 3). The total number of satellites on sky for the current four MEO constellations (Galileo, Glonass, GPS, and Beidou) is 111 and the total number of satellites expected to be launched on sky in the next five years for the three considered LEO constellations (OneWeb, Kuiper, and Starlink) is 44732. The results in Fig. 3 show that joint processing of LEO signals is able to achieve a GDOP-level significantly lower than 1, and on average 2.5 times lower than MEO. Additionally, we have also calculated the average number of satellites per Earth point: by combining only three LEO mega-constellations, one can get an average number of satellites in view of 2658 satellites, while the average number for the combined four GNSS systems is 35. The significant amount of visible future LEO satellites per Earth point can be a rich source of novel positioning methods, besides the traditional code and Doppler positioning, e.g., via Machine Learning (ML) based on beam patterns, as addressed in sub-section III-C.

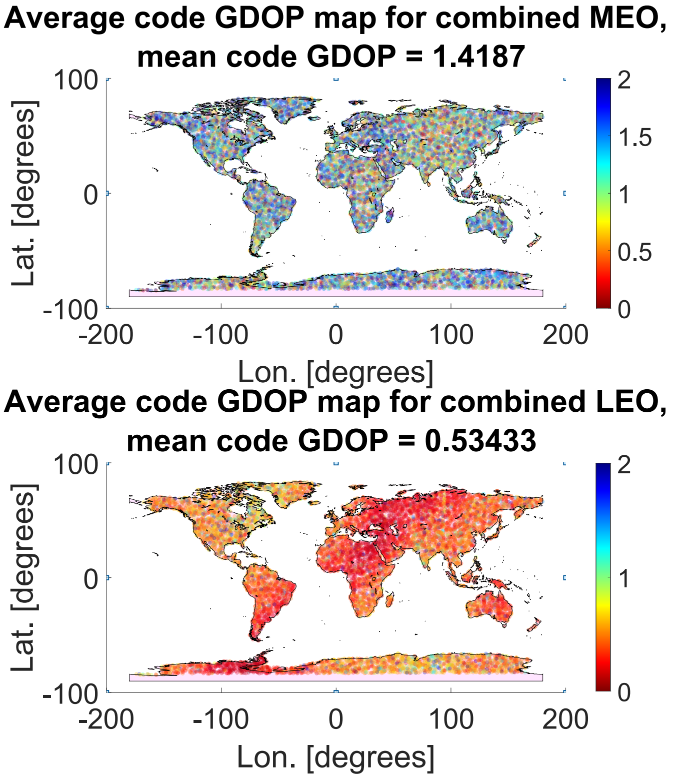

Fig. 3: GDOP for combined MEO GNSS (GPS, Galileo, BeiDou, and Glonass, upper plot) and LEO (Kuiper, Oneweb, and Starlink, lower plot).

B. *Receiver processing*

One of the main issues in the receiver design for opportunistic navigation using LEO satellites is the absence of user positioning parameters in the transmitted signal. Instead of relying on such a broadcast, as it is the case with MEO GNSS, additional sources are used to obtain missing positioning information. If the Doppler shift of the LEO satellite carrier signal is to be used for positioning, the receiver's positioning computation algorithm needs to be designed in a different manner than MEO GNSS receivers, to measure, combine, and process the Doppler shifts of all LEO visible satellites. Such receiver algorithm would also need to account for the unknown clock drift between the satellite clock and receiver clock, as well as for the unknown position and velocity of each visible satellite. Common solutions are to obtain the satellite's state from the Two Line Element (TLE) files, likely to be available in open access, but the satellite position accuracy via TLE is typically poor and solutions to overcome this error source are needed. Furthermore, additional sensors such as altimeters or inertial navigation sensors may provide user altitude information. The computation of position and clock drift may be done, e.g., by using extended Kalman filter [8].

External information may be integrated within a LEO receiver if a Software Defined Radio (SDR) is used. This is part of the appeal of opportunistic navigation, because the components may be Commercial-off-the-shelf (COTS). As shown in previous sub-section, LEO signals tend to have a greater C/N_0 and a better GDOP than MEO signals and these are appealing features to support LEO-based opportunistic navigation at the receiver end. Further details may be found in [8], [2] and references therein. The higher-frequencies LEO constellations will require better performing electronics in order to handle the faster changing signal. This typically comes at a higher cost. Moreover, larger bandwidth is available at higher carrier frequency bands compared to GNSS L-band. A larger bandwidth requires more complex and more costly band-pass filters at the receiver front-end. Alternatively, sub-band or filter-bank-based processing can be studied. The larger bandwidth in LEO may be an advantage if information of the signal characteristics are known and thus it could be exploited for navigation, as wider bandwidths ensure higher accuracies in time-based positioning. Multiple frequencies will also provide challenges for antenna design.

C. Massive MIMO for LEO-based positioning

The implementation of Massive MIMO (mMIMO) in LEO satellites has not started yet as the topic is still under research [9], [10]. However, the introduction of mMIMO beamforming can leverage LEO satellites not only for the regular satellite-Earth communications but also as SoO for positioning. The concept of mMIMO is implemented by the usage of multiple antenna arrays (1000 or more antenna elements), separated by a distance equivalent to half the wavelength, instead of utilizing single antenna systems, hence exploiting the multipaths. This setup has numerous advantages which can enhance the LEO-based localization. The use of spatially multiplexed antennas improves the uplink and downlink throughputs, as it increases the capacity, quality of service, and the data rate of the channel link [9]. One of the main advantages of the beamforming is the extension of the coverage area on Earth per each LEO satellite by using space-time block coding which maximizes the number of user terminals, as shown in Fig. 4. This beamforming concept can be additionally used in the context of positioning, in order to derive certain patterns of beams that are visible only in a certain point of the Earth at a certain time. By combining ML algorithms with such beamforming information, one could also create beamforming-based positioning, a new concept that remains to be investigated. Additionally, the use of numerous antennas in beamforming helps in focusing the energy, thus it improves the efficiency and decreases the susceptibility to jamming and interference.

As a potential challenge, the mMIMO use in LEO satellites comes at higher costs, as they require advanced resources for the signal processing both at the transmitter and the receiver side, in order to be able to solve complex algorithms in the software segment of the system. In addition, complex electronic components are needed at satellite side to control the massive number of antennas in the hardware segment. Consequently, the power budget of mMIMO receivers can be limited due to the large power demand of mMIMO ML processing. This imposes technical limitations and additional costs on the consumer-level receiver devices which could be overcome at long-term with the advent of zero-energy devices (i.e., devices that harness the energy from the environment and interfering signals and are able to self recharge the batteries).

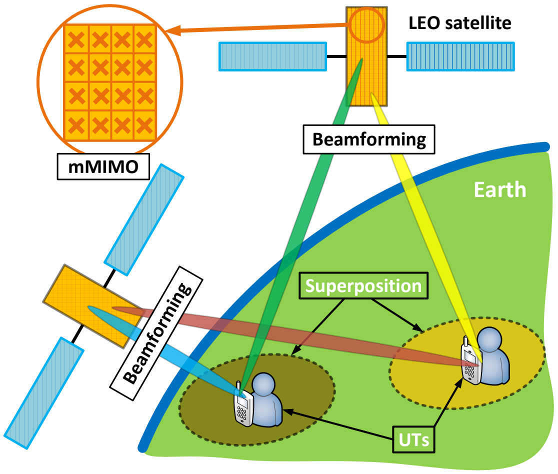

Fig. 4: Principle of mMIMO-beamforming use in LEO satellites.

IV. CHALLENGES, OPPORTUNITIES, AND SOLUTIONS TOWARDS EQUAL ACCESS TO SEAMLESS PNT SERVICES

Seamless PNT services refer to location-based services relying on both indoor and outdoor localization. While GNSS can solve the outdoor access in most areas nowadays, some challenging outdoor scenarios such as regions with heavy vegetation and/or hilly terrains, as well as indoor scenarios still need equal-access positioning services. Challenges towards such an equality of access are, for example, the cost or difficulty of building adequate and dense-enough terrestrial infrastructure, the desire to preserve a natural habitat or a greenfield untouched by infrastructure, and the scenarios where current GNSS solutions fail to offer a robust enough positioning, due to various types of intentional or unintentional interference. In terms of positioning, the main differences between indoors and outdoors are: i) lower received signal strengths indoors due to wall absorption, signal scattering, and multipath propagation;

ii) multipath-rich environments and absence of Line of Sight (LOS) propagation; and iii) fast-changing propagation scenarios due to people movements, doors closing and opening, changes in furniture, etc. A significant limitation towards equal access to location-based services is the access to infrastructure, such as WiFi/BLE/UWB/cellular access points, or other infrastructure. Infrastructure-less positioning solutions, such as magnetic-field based positioning, can carry a hidden cost of creating and maintaining training databases, as such methods typically rely on offline data collection for training ML algorithms. The alternative could be the use of universally accessible signals, such as those coming from satellite systems with wide Earth coverage. Both MEO GNSS and LEO mega constellations have currently excellent coverage outdoors [1] and even higher coverage is expected in the next 5-10 years with the future LEO constellations.

When focusing on indoor location-based services, security of the solution is of utmost importance. MEO GNSS is currently addressing security features through dedicated authenticated signals, e.g., through the Galileo Open Service Navigation Message Authentication (OSNMA). LEO systems support also various authentication mechanisms, such as physical layer security [11], [12] or through the use of ML [13], which are promising also in the context of positioning.

An additional challenge is the tradeoff between the number of satellites and achieved coverage, as it takes several LEO satellites on orbit to match the footprint of one MEO satellite. This challenge is easily overcome by the huge total number of LEO satellites to be launched on sky in the next few years [1]. Another challenge is that smaller satellites and cheaper transmitters in LEO systems result in less stable clocks, higher clock inaccuracies, higher phase noises and I/Q imbalances, and higher non-linearities of the components than in MEO, which pose additional constraints on the LEO-based PNT. Nevertheless, such hardware inaccuracies enable physical-layer-based authentication, such as Radio Frequency fingerprinting (RFF) [12] or ML algorithms [13] that use the hardware imperfections of each satellite transmitter as a modality to identify if a transmitter is genuine or not.

A summary of challenges, opportunities, and solutions are listed in Table I.

V. LEO MEGA-CONSTELLATIONS AND BUSINESS MODELS

The emergence of LEO mega-constellations are making satellite connectivity 2.0 successful. Large LEO-based satellite internet constellations need careful cost planning to ensure long-term viability - including low-cost spacecraft manufacturing, launch, ground and user equipment. The mega-constellations show signs of truly transforming both the business-to-consumer and business-to-business communications markets, reaching both the hard-to-reach consumers as well as the masses and related services. The worldwide pandemic has also significantly increased the demand for internet connectivity, strengthening the economic viability of satellite internet via LEO.

The positioning market is already forecast to grow dramatically according to various market reports, such as those provided by ReportLinker/MarketandMarket reports from 2019 – 2020. Ubiquitous localization as side products of the connectivity service offered by the mega-constellations would likely cause an even larger increase in innovation from developers/start-ups, driving the market further. The strength of LEO constellations providing PNT is that the service can be designed to meet the specific needs of the markets, providing a market-driven solution rather than retrofitting legacy systems [14]. As a weakness, [14] mentions that such a business case can then likely not be closed, due to the fact that a dedicated system will be very expensive and thus economically less attractive. However, a hosted payload on the mega-constellations that are already planned to be launched is a very promising approach.

VI. SUMMARIZING DISCUSSIONS AND CONCLUSIONS

Modern LEO mega constellations can bring performance and energy efficiency to a next level if re-purposed for the indoor positioning as SoO, by exploiting, code, Doppler, and beam-based measurements from space. The high number of LEO satellites and their proximity to Earth, as well as easier support for authentication/security signals are features in favour of LEO, but their use of large carrier frequencies (e.g., 12 MHz or higher) can act as deterrents by introducing additional path losses and indoor penetration losses. A big advantage of LEO mega constellations as SoO for localization lies in their potential zero-cost worldwide equal access to signals from space, which would remove the need of a specific indoor infrastructure and would rely on tailored SDRs. The target performance criteria for positioning should be framed as a multi-dimensional problem of reaching accurate positioning, high coverage, and high energy efficiency, while still preserving the original communications targets for which LEO mega-constellations were launched (e.g., high throughput and low latency in communications) as well as ensuring full security and privacy to the end users. If some of the future LEO mega-constellations will also host GNSS transceivers on-board, additional hybrid LEO-GNSS solutions could be envisaged, with on-board GNSS transceivers offering synchronization information, clock bias corrections, as well as assisted data, such as atmospheric corrections. Data fusion and hybridization solutions can rely on classical algorithms such as Kalman and particle filtering or can make use of the advances in ML field and remain a topic of future investigation. Robust and accurate positioning using LEO mega-constellations can leverage new approaches compared to the traditional trilateration, especially when combining code-Doppler measurements. To cope with less stable clocks and challenges in precisely locating the satellites, mathematical and computational methods traditionally applied in other contexts could be extended to find fast, accurate, and robust solutions for the multilateration problem. The multi-beamforming capacity of future LEO satellites also offer the promise of fingerprinting-based positioning, where combinations of beams from various satellites will carry a unique imprint on Earth and could be identified through ML algorithms. Studies regarding the requirements on the beam width limits to ensure the best location fingerprinting capabilities are currently missing from the existing literature and remain the topic of future investigations.

Opportunities	**Challenges**	**Solutions**
Lower cost to build and launch than MEO satellites	Current orbital planes/orbit altitudes not optimized for PNT	A combination of Doppler, angle, RFF & code-based positioning could harness best the capabilities of LEO SoO. With the advent of future wireless devices supporting the integration of terrestrial and satellite signals at the receiver side, additional localization tasks could be implemented as software adds-ons. Waveform specificity of LEO signals could be circumvented via non-time-based localization solutions.
Large number of satellites from various LEO mega-constellations	LEO constellations are not typically synchronized or built to be inter-operable; code-based positioning approaches may be challenging	Hybridizing Doppler-based and angle-based positioning from all available constellations; on-board GNSS receivers to help synchronization issues between LEO satellites; co-design of LEO services for increased interoperability
High dynamics and higher satellite speeds may enable better Doppler-based positioning than MEO satellites	Ephemeris broadcast to meet the positioning targets may be hindered by proprietary restrictions; Doppler/carrier-phase ambiguities must be solved	Blind Doppler estimation and multi-system positioning to deal with ambiguities and incomplete information; simultaneous transmitter-receiver location through geometrical modeling
Global coverage, increased visibility	Minimum four satellites per Earth position must be visible; global coverage so far has been optimized for single-satellite visibility for communication purposes only	Combining the signals coming from various mega-constellations
Potentially lower path losses than with MEO satellites due to closer proximity to Earth	Indoor additional losses need careful modeling/mitigation	Beamforming/multi-antenna LEO capabilities could be used for enhanced multipath mitigation
Rich transmitter-hardware features due to imperfections of the transmitter payload chain (power amplifiers, mixers, etc.) to serve as authentication/security features	Time-based positioning methods are more challenging if clock inaccuracies are high	Doppler/angle-based positioning to compensate for time-based estimation inaccuracies or replace completely the timing-based estimates for low-cost receivers supporting only certain waveforms
Narrowband modulations to enable lower-energy receiver processing, e.g., due to faster acquisition times, and better link budgets than the wideband modulations used in MEO GNSS	Time-based positioning accuracy increases with higher available bandwidth; narrowband modulations may not reach high time-delay estimation accuracy	Time/code-based positioning complemented with angle/Doppler-based positioning, by taking advantage of high satellite speeds and rich beamforming structures; ML-based positioning can also be envisaged with the rich spatial data from LEO
Possibility of introducing authentication and encryption signals, unconstrained by legacy MEO signals	Authorized access may be limited by the LEO service provider	Physical layer authentication mechanisms such as RFF/ML may complement the signals with authorized use

TABLE I: Opportunities, challenges, and solutions for LEO mega-constellations as future SoO for equal-access localization.

In conclusions, LEO mega-constellation carry a yet-to-be-explored potential for equal-access indoor navigation, especially in remote/un-populated areas with indoor dwellings and factories, where current indoor-positioning solutions are not affordable. Thousands of LEO satellites belonging to various mega constellations will span over the Earth within the next few years, offering worldwide wireless signals at low-to-moderate costs to the end users equipped with a LEO receiver. The main capex costs of the ground and sky infrastructure are to be covered by the LEO-systems manufacturers, and their main revenue source is likely to come from communication-based services, such as mobile broadband or IoT applications. At the same time, a niche research domain, is the use of such LEO signals as SoO for indoor positioning, where low-to-moderate cost receivers can be designed to capture LEO signals on various nearby carrier frequencies and apply code, Doppler, angle, and beam-based positioning algorithms to locate the users indoors.

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